FILE COPY
NO 1

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 438

EXPERIMENTS ON THE DISTRIBUTION OF FUEL IN FUEL SPRAYS

By DANA W. LEE

THIS DOCUMENT ON LOAN FROM THE FILES OF
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
LANGLEY AERONAUTICAL LABORATORY
LANGLEY FIELD, HAMPTON, VIRGINIA
RETURN TO THE ABOVE ADDRESS.
REQUESTS FOR PUBLICATIONS SHOULD BE ADDRESSED
AS FOLLOWS:
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
1512 H STREET, N. W.
WASHINGTON 25, D. C.

1932

For sale by the Superintendent of Documents, Washington, D. C - - - - - - - - - - - - - - - Price 10 cents

AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 $= 32.1740$ ft./sec.^{2}

m, Mass $= \frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 750 mm $= 0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m^3 $= 0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $= \frac{1}{2}\rho V^2$.

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force.

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting (relative to thrust line).

Q, Resultant moment.

Ω, Resultant angular velocity.

$\rho\frac{Vl}{u}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.

C_p, Center of pressure coefficient (ratio of distance of $c.\ p.$ from leading edge to chord length).

α, Angle of attack.

ϵ, Angle of downwash.

α_o, Angle of attack, infinite aspect ratio.

α_i, Angle of attack, induced.

α_a, Angle of attack, absolute. (Measured from zero lift position.)

γ, Flight path angle.

REPORT No. 438

EXPERIMENTS ON THE DISTRIBUTION OF FUEL IN FUEL SPRAYS

By DANA W. LEE
Langley Memorial Aeronautical Laboratory

132797—32——1

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING, WASHINGTON, D. C.

(An independent Government establishment, created by act of Congress approved March 3, 1915, for the supervision and direction of the scientific study of the problems of flight. Its membership was increased to 15 by act approved March 2, 1929 (Public, No. 908, 70th Congress). It consists of members who are appointed by the President, all of whom serve as such without compensation.)

JOSEPH S. AMES, Ph. D., *Chairman*,
President, Johns Hopkins University, Baltimore, Md.
DAVID W. TAYLOR, D. Eng., *Vice Chairman*,
Washington, D. C.
CHARLES G. ABBOT, Sc. D.,
Secretary, Smithsonian Institution, Washington, D. C.
GEORGE K. BURGESS, Sc. D.,
Director, Bureau of Standards, Washington, D. C.
ARTHUR B. COOK, Captain, United States Navy,
Assistant Chief, Bureau of Aeronautics, Navy Department, Washington, D. C.
WILLIAM F. DURAND, Ph. D.,
Professor Emeritus of Mechanical Engineering, Stanford University, California.
BENJAMIN D. FOULOIS, Major General, United States Army,
Chief of Air Corps, War Department, Washington, D. C.
HARRY F. GUGGENHEIM, M. A.,
The American Ambassador, Habana, Cuba.
CHARLES A. LINDBERGH, LL. D.,
New York City.
WILLIAM P. MACCRACKEN, Jr., Ph. B.,
Washington, D. C.
CHARLES F. MARVIN, M. E.,
Chief, United States Weather Bureau, Washington, D. C.
WILLIAM A. MOFFETT, Rear Admiral, United States Navy,
Chief, Bureau of Aeronautics, Navy Department, Washington, D. C.
HENRY C. PRATT, Brigadier General, United States Army,
Chief, Matériel Division, Air Corps, Wright Field, Dayton, Ohio.
EDWARD P. WARNER, M. S.,
Editor "Aviation," New York City.
ORVILLE WRIGHT, Sc. D.,
Dayton, Ohio.

GEORGE W. LEWIS, *Director of Aeronautical Research.*
JOHN F. VICTORY, *Secretary.*
HENRY J. E. REID, *Engineer in Charge, Langley Memorial Aeronautical Laboratory, Langley Field, Va.*
JOHN J. IDE, *Technical Assistant in Europe, Paris, France.*

EXECUTIVE COMMITTEE

JOSEPH S. AMES, *Chairman.*
DAVID W. TAYLOR, *Vice Chairman.*

CHARLES G. ABBOT.
GEORGE K. BURGESS.
ARTHUR B. COOK.
BENJAMIN D. FOULOIS.
CHARLES A. LINDBERGH.
WILLIAM P. MACCRACKEN, Jr.
CHARLES F. MARVIN.
WILLIAM A. MOFFETT.
HENRY C. PRATT.
EDWARD P. WARNER.
ORVILLE WRIGHT.

JOHN F. VICTORY, *Secretary.*

E R R A T A

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL REPORT NO. 438

EXPERIMENTS ON THE DISTRIBUTION OF FUEL IN FUEL SPRAYS

Pages 8-16 incl.: The values given in the time scales of Figures 6, 8 to 12, and 15 to 20 should be divided by two.

The values given in the time scales of Figures 13 and 14 should be divided by four.

The values given in the linear (vertical) scales of Figures 13 and 14 should be divided by two. The linear scales of the other figures are correct.

The value of the chamber-air density given with Figure 10 should be 0.60 pound per cubic foot.

REPORT No. 438

EXPERIMENTS ON THE DISTRIBUTION OF FUEL IN FUEL SPRAYS

By Dana W. Lee

SUMMARY

The distribution of the fuel in sprays for compression-ignition engines was investigated by taking high-speed spark photographs of fuel sprays produced under a wide variety of conditions, and also by injecting them against pieces of Plasticine. A photographic study was made of sprays injected into evacuated chambers, into the atmosphere, into compressed air, and into transparent liquids. Pairs of identical sprays were injected counter to each other and their behavior analyzed. Small high-velocity air jets were directed normally to the axes of fuel sprays, with the result that the envelope of spray which usually obscures the core was blown aside, leaving the core exposed on one side.

The results showed that the distribution of the fuel within the sprays was very uneven. Under engine-operating conditions the fuel was subdivided into many small particles by the time it had penetrated 0.75 inch. In the cores of the sprays, these particles had a high velocity relative to the air in their immediate vicinity, but as their velocity was reduced, they were forced out of the core and formed the spray envelope. The shape of the central core varied with the density of the chamber air, becoming shorter and thicker with increasing air density.

INTRODUCTION

Because of the great importance of fuel distribution in the development of light-weight compression-ignition engines, this series of experiments was undertaken for the purpose of obtaining more information on the distribution of the fuel within fuel sprays for this type of engine. There are two general methods available for such an investigation: The separation of the sprays into parts, followed by a determination of the amounts of fuel in each part, and the high-speed photography of sprays produced under conditions especially arranged to reveal the desired information. The first method has been successfully used at the Pennsylvania State College with sprays from plain cylindrical nozzles (references 1 and 2), and the results show that the fuel concentration was greatest in the center of the spray. Many early spark photographs made by the National Advisory Committee for Aeronautics also show a core of concentrated fuel but the density of the spray cloud was so great that little could be learned of the internal structure of the sprays.

In the present experiments, the photographic method was extended and improved by decreasing the exposure time, and by injecting the fuel under conditions which had not been used before at this laboratory. These experiments were conducted during the summer of 1931 by the National Advisory Committee for Aeronautics at Langley Field, Va.

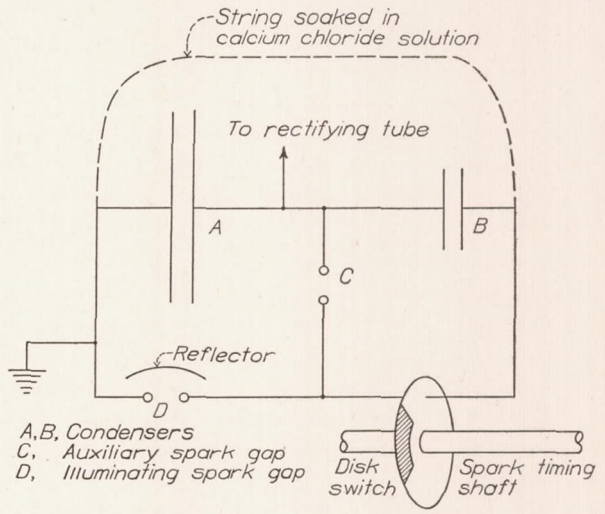


FIGURE 1.—Circuit used to produce illuminating sparks of short duration

APPARATUS AND TEST METHOD

A complete description of the spray-photography equipment used in this investigation is given in reference 3. Briefly, the spray is illuminated by a series of spark discharges, and the images are focused on a moving film by a lens. The duration of the individual spark discharges has never been accurately determined, but the amount of blurring in some of the photographs indicates a duration of from 0.00001 to 0.000001 second.

During part of this investigation, the spark-producing circuit was replaced by that shown in Figure 1. This circuit is similar to those used in electric stroboscopes and for the photography of bullets in flight. The duration of the spark discharge in such circuits is said to be of the order of 0.0000001 second. (Refer-

ence 4.) The high-voltage condensers A and B were charged to a potential of 30,000 volts by using a transformer and a rectifying tube. A cotton string wet with calcium chloride solution formed a high electrical resistance and was used to keep the two condensers at the same potential. The spark was timed by a disk switch on a shaft connected through an adjustable coupling to the camshaft controlling the fuel injection. When the switch was closed by a rotation of the shaft, condenser B discharged across gap C. The width of the two spark gaps was so adjusted that condenser A would not discharge across both of them until after the air in gap C had been ionized by the discharge of condenser B. The discharge of condenser A across gap D furnished the light for photographing the spray, gap C being shielded from the camera. The copper connecting wires were about three thirty-seconds inch in diameter and were made as short as possible to minimize the resistance of the circuit. The spark-gap points were made of copper instead of the magnesium regularly used, to reduce the afterglow of metallic vapor that follows the breakdown of the spark discharge. As this circuit delivered only a single spark, the photograph was taken on a stationary film. Sets of photographs showing the various stages in the development of the sprays were made by using a different spark timing for each photograph. The high-speed spark circuit was used during an investigation of the effect of the density of the chamber air on the distribution of the fuel in fuel sprays. The photographs were clearer than those made with the regular circuit, revealing several new features of spray structure and formation.

The regular spark circuit was used to take several other series of spray photographs. In one series, each injection was composed of two separate sprays directed toward each other and impinging in the center of the chamber. A T connection was inserted in the injection line, and pieces of steel tubing of equal length and diameter were connected to the injection valves. As these valves were of the same design, only a slight adjustment of the valve-opening pressures was necessary to cause the sprays to emerge from the two nozzles simultaneously. Open nozzles were also used, and these were so arranged that the distance between the nozzles could be changed. Sketches showing the type of injection valve and open nozzles tested may be found in reference 5. An orifice diameter of 0.020 inch was used for all tests except those with the centrifugal-type sprays; for those it was 0.022 inch.

The alignment of the sprays was checked by pumping fuel through the nozzles at a pressure so low that unbroken jets of fuel were formed. These jets met at the center of the chamber and formed a disk of fuel about an inch in diameter. The plane of this liquid disk was at right angles to the axis of the fuel jets, showing that the two nozzles were in good alignment.

For another series of photographs a tube was brought through the top of the spray chamber, its end closed, and a small hole drilled in this closed end. The other end of the tube was connected to a compressed-air reservoir, so that a strong jet of air was produced in the spray chamber. This jet was directed normal to the axis of the fuel spray at different distances from the fuel nozzle. Hand valves were placed between the compressed-air reservoir and the air-jet orifice, and between the spray chamber and the atmosphere. The injection pressure of the air jet and the chamber-air density could be regulated to the desired values by adjusting these valves. Fuel and air-jet injection pressures and chamber-air pressures were measured with reference to the atmospheric pressure, and are so expressed in this report.

The temperature of the chamber air was approximately the same as that in the room for all tests. Changes in its density were secured by changing its pressure. Densities less than atmospheric were obtained by evacuating the chamber with a vacuum pump, and those greater than atmospheric by connecting the chamber to a compressed-air reservoir.

Experiments on the relative penetrating power of different sprays, and of the different parts of the same spray were made by injecting them against smooth-surfaced pieces of Plasticine, a proprietary substitute for modeling clay. The depths and shapes of the impressions made in the Plasticine were compared for injections from plain cylindrical nozzles, and from nozzles having helical grooves in the valve stem. Different injection pressures and chamber-air densities were used, and the Plasticine was placed at different distances from the nozzles. This method of studying sprays was found to be very satisfactory, and it is recommended as a simple and valuable test of the energy distribution of the fuel within fuel sprays.

A high-grade Diesel fuel having a specific gravity of 0.86 at 80° F., and a viscosity of 0.0221 poise (35.0 seconds Saybolt Universal) at 100° F. and atmospheric pressure was used in all the tests.

RESULTS AND DISCUSSION

EFFECT OF AIR DENSITY ON THE DISTRIBUTION OF FUEL IN SPRAYS

The formation of fuel sprays.—The exact process by which fuel injected through small nozzles is atomized to form a spray has long been a matter of controversy. Some investigators have explained atomization on the basis of frictional forces between the fuel and the air, and others have maintained that the atomization is essentially complete before the fuel leaves the nozzle. Experiments made at this laboratory (reference 6) show that the density of the air into which the fuel is injected has little effect on the ultimate fineness of the atomization. Later experiments (reference 7) show that although the final results may be the same, an increase in the air density causes the atomizing process to take place closer to the nozzle. Moreover, it is shown that the atomization of the fuel is primarily caused by air friction. The fuel emerges from

the nozzle as a solid column, but is soon torn into shreds or ligaments as it passes through the dense air. These ligaments are very quickly transformed into drops by the force of the fuel surface tension.

Computations of the velocity and penetration of single fuel drops injected into dense air have been made by Kuehn. (Reference 8.) He showed that for the range of injection velocities, drop sizes, and combustion chamber-air densities commonly used in airless injection engines, in no case would a single fuel drop penetrate the air much more than 1 inch. The fact that fuel sprays penetrate much farther he concluded to be due to the mass effect of the large number of particles that they contain. In the central part of the sprays, the drops and ligaments are so closely spaced that most of them do not travel through still air, but are in air which has been disturbed by preceding fuel particles. The leading ones set up an air current in the direction in which they are moving, so that the later ones, although not traveling a greater distance relative to the air, actually reach points farther from the nozzle.

The high-speed motion pictures of fuel sprays from cylindrical nozzles that have been made at this laboratory show that the fuel in the central core of the spray travels faster than that in the surrounding envelope. This fact indicates that the fuel particles in the core have a high velocity relative to the air in their immediate vicinity and cause it to move in the same direction. After they have lost most of this relative velocity they are forced aside by the on-coming column of air and fuel behind them.

Plasticine target tests.—The foregoing explanation of spray formation was supported by the results of the experiments with Plasticine targets. One of the preliminary experiments consisted of directing a jet of air against the Plasticine. It was found that no impression was made no matter how close the air nozzle was brought to the Plasticine surface, or how great an air-injection pressure was used. When fuel sprays were injected against the targets, impressions were formed having diameters less than the diameters of the sprays at the sections intersected by the targets. In the sprays, therefore, it was the fuel rather than the air that deformed the Plasticine, and the fuel in the central cores of the sprays had much more energy than that in the envelopes.

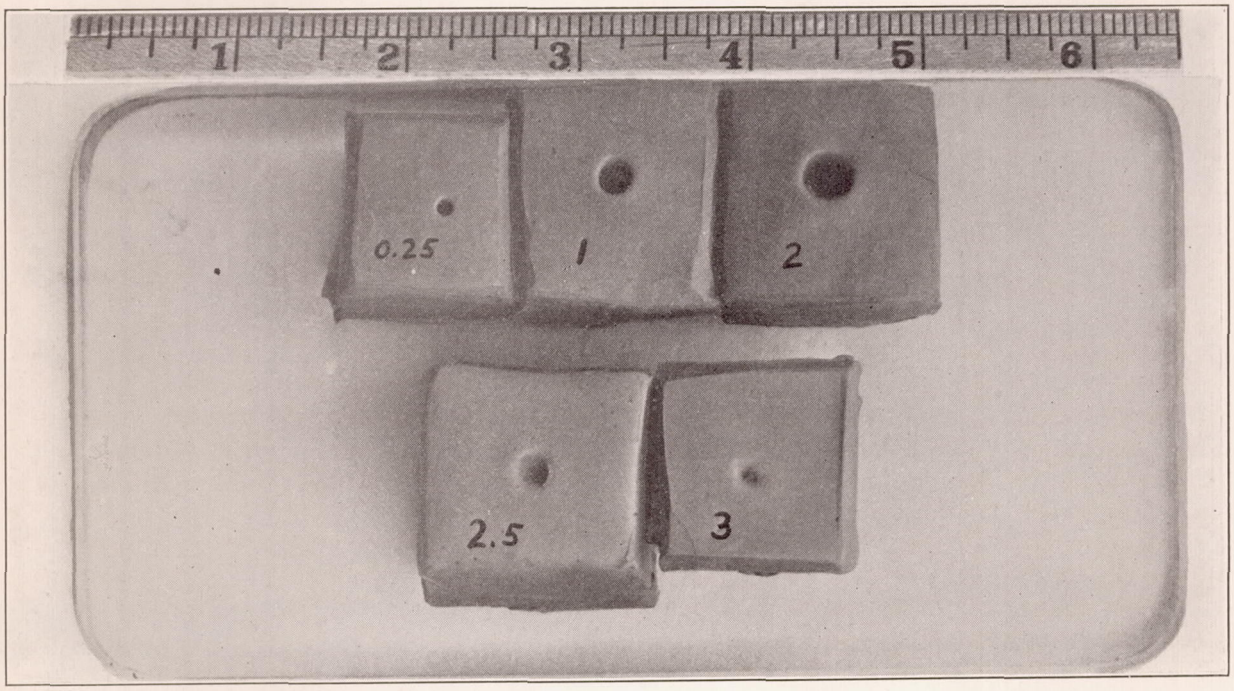


FIGURE 2.—Impressions made in Plasticine by fuel sprays injected through air having a density of 1.1 pounds per cubic foot

Fuel-injection pressure, 4,000 pounds per square inch; valve-opening pressure, 3,500 pounds per square inch. The number beside each impression indicates the distance in inches between the nozzle and the Plasticine.

Figure 2 is a photograph of a series of impressions made in Plasticine by sprays from a plain cylindrical nozzle. In the following table are listed the diameters and depths of the impressions, and in the last column are given the outside diameters of a spray, produced under the same conditions, and measured from a spray photograph at corresponding distances from the nozzle.

Distance from nozzle to target	Diameter of impression	Depth of impression	Outside diameter of spray from photograph
Inches	*Inch*	*Inch*	*Inches*
0.25	0.08	1.0	0.25
1.0	.20	.9	.50
2.0	.25	.5	.75
2.5	.20	.1	.94
3.0	.12	.05	1.10

A comparison of the second and fourth columns of the table shows that although the general outline of the spray was a cone, the core of rapidly moving fuel in the center increased in diameter until it reached a point about 2 inches from the nozzle, and then diminished. Targets placed 3.5 inches from the nozzle showed only a shallow impression; at 4 inches no impression at all could be seen. At this distance, so much of the kinetic energy of the fuel had been transferred to the air that the spray could make no mark on the target.

For each of these tests the thickness of the Plasticine was made sufficient to stop the fuel completely. The bottom of the impressions was always conical in form, indicating roughly the distribution of energy in the spray core. In this connection, the tests made at the Pennsylvania State College (references 1 and 2) on the distribution of fuel within sprays from cylindrical nozzles are of interest. The two methods supplement each other very well; the N. A. C. A. tests give results for the core of the spray, and the Pennsylvania State College tests give data for the envelope.

The diameters given in the table are those at the surface of the Plasticine. An examination of the deeper impressions showed that their diameter increased somewhat below the surface. The enlargement was probably caused by the blasts of air that were carried into the holes by the fuel particles. In another series of tests, thin slices of Plasticine were used, backed by wire screening. This arrangement allowed the fuel spray to pass through the target, leaving a hole that more accurately indicated the core diameter. For the same conditions to which the results of the table apply, and at the same distances from the nozzle, the diameters of the impressions were 0.04, 0.08, 0.14, 0.18, and 0.16 inch, respectively.

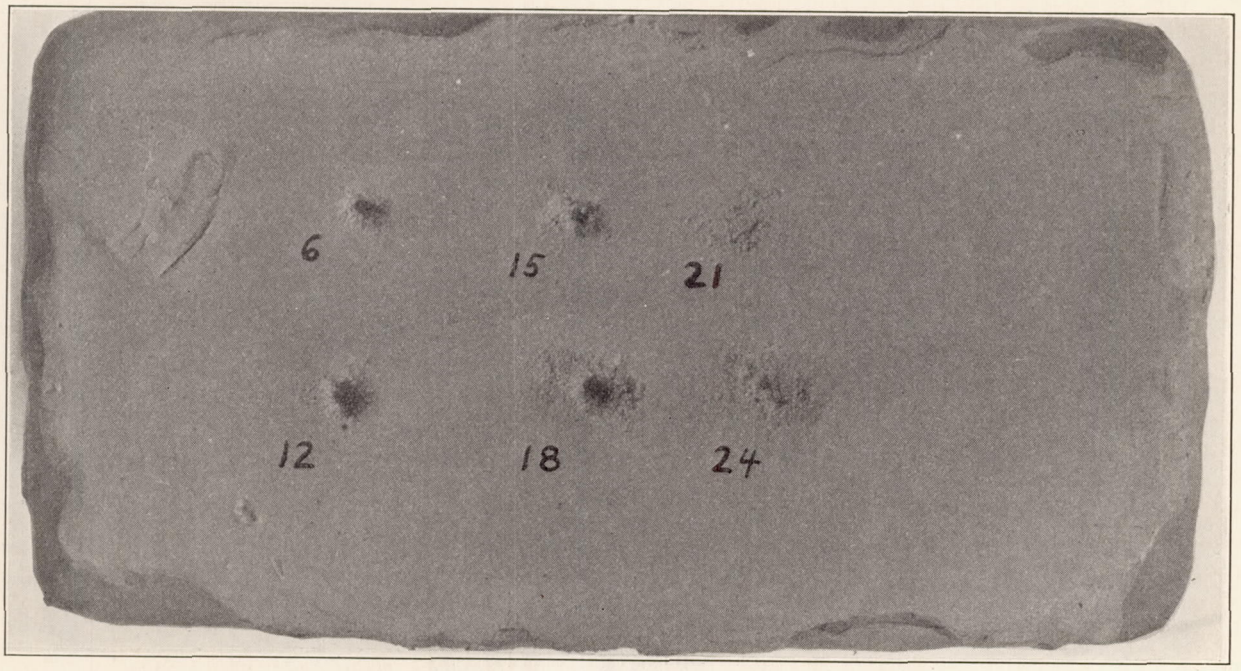


FIGURE 3.—Impressions made in Plasticine by fuel sprays injected through air having a density of 0.076 pound per cubic foot

Fuel-injection pressure, 4,000 pounds per square inch; valve-opening pressure, 3,500 pounds per square inch. The number beside each impression indicates the distance in inches between the nozzle and the Plasticine

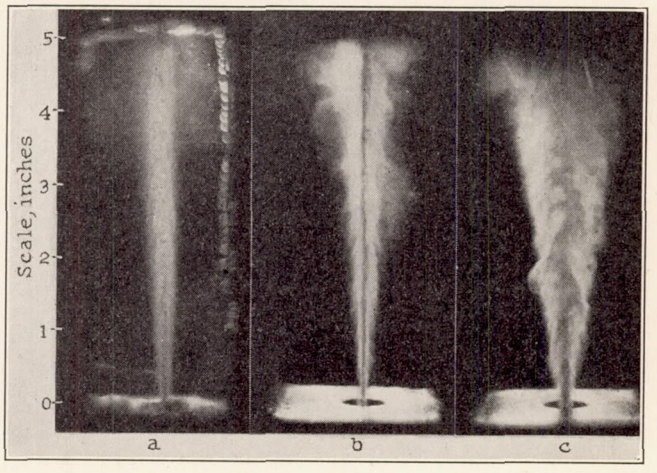


FIGURE 4.—High-speed spark photographs of fuel sprays injected into air having different densities

Injection pressure, 4,000 pounds per square inch; chamber-air density, (*a*) 0.0005 pound per cubic foot, (*b*) 0.076 pound per cubic foot, (*c*) 1.1 pounds per cubic foot.

Figure 3 is a photograph of the impressions made in Plasticine by sprays injected into the atmosphere. The form of the impression varies from an almost straight-walled hole 0.10 inch in diameter and about 0.50 inch deep at the 6-inch distance, through a series

of trumpet shapes having increasing amounts of flare and less depth, until at 24 inches the impression is of almost uniform depth.

Spark photographs showing the effect of air density.—The photographs of Figure 4, which were made with the high-speed spark circuit shown in Figure 1, show the effect of the density of the chamber air on the formation of fuel sprays from a plain cylindrical nozzle. In this case, the dispersion of the spray in the vacuum was about the same as in the atmosphere, but increased when the air density was raised to values above atmospheric. When other cylindrical nozzles and other injection pressures were used, it was found that the dispersion of the sprays in vacuum varied greatly. In some cases they were as well dispersed as the one shown in Figure 4a; in other cases the fuel remained in a solid column with no dispersion. As practically no air was present, any dispersion of the fuel must have been the result of turbulent flow in the jet. Such turbulence would vary with orifice diameter, fuel velocity, and roughness of the nozzle, producing varying degrees of spray dispersion. A comparison of photographs made at different stages of injections into the evacuated chamber shows that all parts of the spray have very nearly the same velocity, as compared with the different velocities prevailing in sprays injected into air.

In Figure 4b the core of a spray injected into the atmosphere is shown quite distinctly, surrounded by the envelope. Streamers of spray are projecting away from the core and downward. These were formed as the spray tip passed these places, the conical tip being continually replaced by fresh fuel coming up the core. When the chamber-air density was raised to 1.1 pounds per cubic foot, the velocity of the spray tip was so greatly reduced that the fuel thrown off completely hid the core. (Fig. 4c.) For this last case, the chamber-air density corresponded to that at top center in an engine with a compression ratio of 14.5.

The high-speed spark photographs of injections into air at atmospheric density gave some interesting results. The chamber air was dense enough to show some effect on the sprays, but not dense enough to cause the core to be hidden. In Figure 5 are shown two photographs of fuel sprays in the atmosphere, the injection pressures being 3,000 and 700 pounds per square inch. In Figure 5a notice the vortices at the edge of the spray, probably caused by the different velocities of the air in the core and the envelope. Also notice in Figure 5b that the core does not appear as a solid jet of fuel, but seems to be broken up.

PENETRATION OF FUEL JETS INJECTED INTO LIQUIDS

As the density of the air into which the sprays were injected was increased, the deceleration of the spray tip became more rapid. However, even when using the greatest air pressure that was safe in the spray chamber, the spray tip was still moving rapidly when it reached the opposite side of the chamber. The effect of a dense medium was obtained without going to dangerously high pressures by using water or glycerin instead of air. The medium itself having been changed, the results can not be strictly compared with those obtained with air, but spark photographs made with the regular spark circuit showed that the shape and general behavior of fuel jets injected into water were similar to sprays injected into compressed air when the same injection valve and nozzle were used. (See fig. 6.) When fuel was injected into water that was at atmospheric pressure, the fuel jet was very narrow and the rate of penetration nearly as high as that in air having a density of 1.1 pounds per cubic foot. When pressure was applied to the water the rate of penetration was much lower, and the jet much broader. Similar results were obtained when the fuel was injected into glycerin.

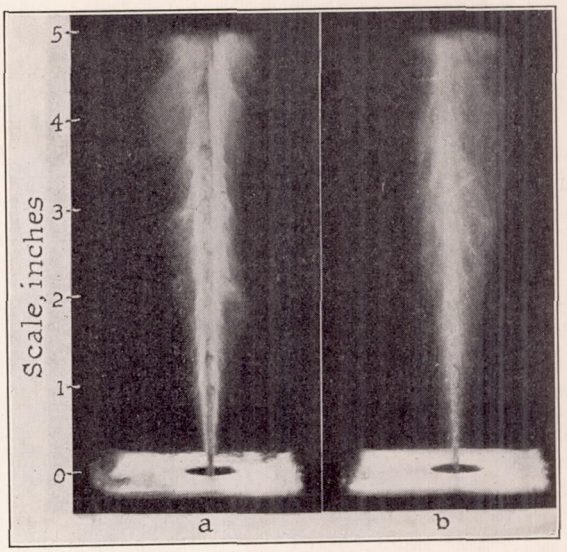
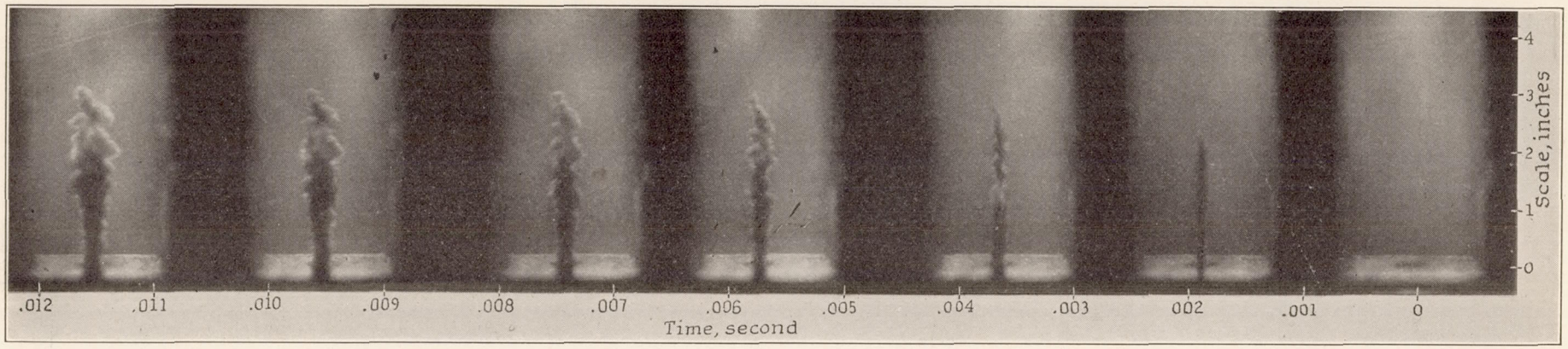


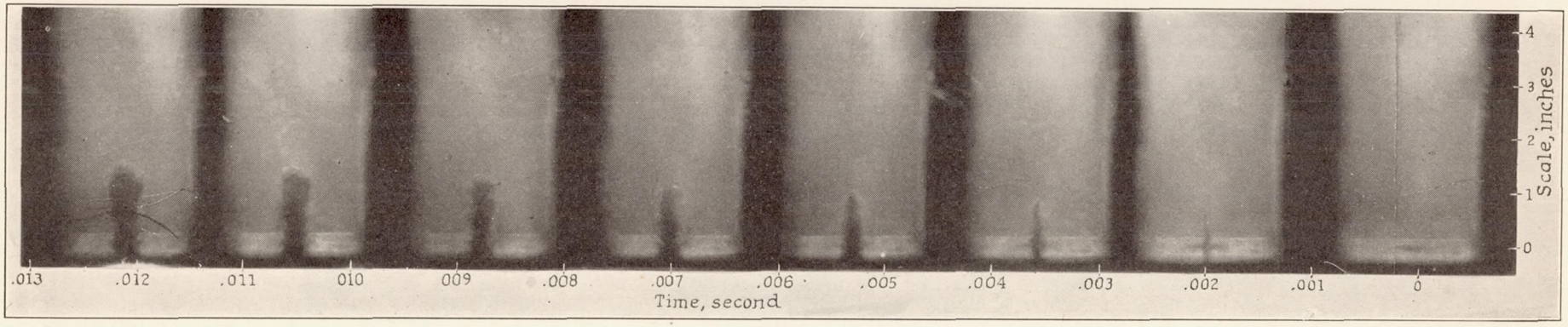
FIGURE 5.—High-speed spark photographs of fuel sprays injected into the atmosphere

Chamber-air density, 0.076 pound per cubic foot; fuel-injection pressure, (*a*) 3,000 pounds per square inch, (*b*) 700 pounds per square inch.

Figure 7 shows the variation in spray-tip penetration with time for fuel injections into water and glycerin having various pressures, and also shows one curve for a spray injected into compressed air for comparison. Notice that the rate of penetration does not decrease uniformly with increasing water pressure, an increase from atmospheric pressure to 15 pounds per square inch having a greater effect than a further increase to 100 pounds per square inch. Injections into gases having various pressures and the same temperature have shown the same trend, but to a lesser extent. (Reference 9.) As the density of a liquid changes very little with pressure, the decrease in the rate of penetration can not be attributed to an increase in the density as it was for gases. Neither can it be



(a)



(b)

FIGURE 6.—Diesel fuel injected into water

Fuel-injection pressure, 2,000 pounds per square inch; chamber-water pressure, (*a*) atmospheric, (*b*) 25 pounds per square inch.

attributed to a change in viscosity in the case of water for the effect of a change of pressure of this magnitude on the viscosity of water is very slight. Only two injections were made into glycerin, but in each case the penetration was greater than with water at the same pressure. This was contrary to expectations, for both the density and viscosity of glycerin are greater than those of water.

Another feature of the curves in Figure 7 is the sudden decrease in their slope after 0.0005 to 0.0015 second. This break probably represents the change from a forward motion of the fuel through the liquid medium to a turbulent movement of mixed fuel and liquid medium.

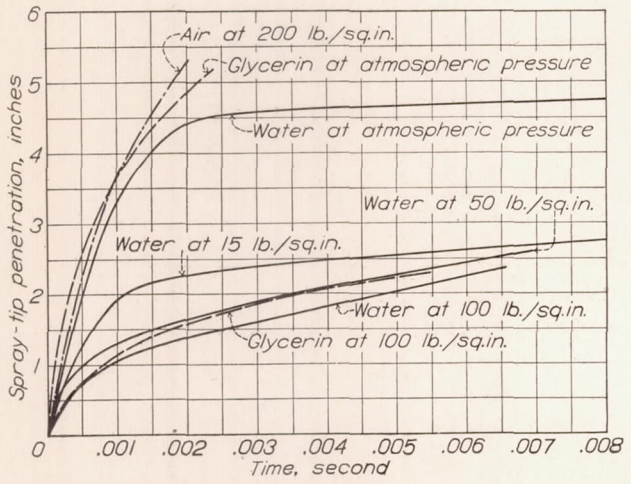


FIGURE 7.—Effect of the liquid pressure on the spray-tip penetration of fuel jets injected into water and glycerin

Diameter of orifice, 0.020 inch; fuel-injection pressure, 4,000 pounds per square inch; valve-opening pressure, 2,000 pounds per square inch.

OPPOSED FUEL SPRAYS

In the experiments with sprays directed against each other, the axes of the two sprays were coincident. Each spray being symmetrical about its axis, similar parts of the two sprays met in the center of the chamber. The result of this meeting, as shown by the spark photographs, can be explained along the lines of the foregoing discussion.

Figures 8 to 11 show four series of spark photographs of such opposed fuel sprays, made with the regular spark circuit. Each series was made with an injection pressure of 4,000 pounds per square inch, but with different chamber-air densities. The distance between the nozzles was 5 inches for this series of photographs, so that the sprays met after each had become 2.5 inches long. With the chamber evacuated (fig. 8) there was some interference between the opposing sprays, but there was no indication of a disk such as was formed when two solid jets were directed against each other. There being practically no air present to hinder the motion of the fuel, the deflected portions of the sprays quickly filled the space around the main jets. With the chamber air at atmospheric pressure (fig. 9) the cores of the sprays again met each other with little interference. In this case, however, the deflected portions were quickly stopped by the air, so that they formed an eddying envelope about the cores.

When the density of the chamber air was increased to 0.60 pound per cubic foot (fig. 10) there was practically no interference between the sprays. They were apparently so well dispersed that the ligaments and drops in each spray passed between those of the other spray. For Figure 11, the chamber-air density was raised to 1.1 pounds per cubic foot. The sprays again passed through each other, but a different kind of interference was shown by the bulging of the envelopes at the meeting point. The appearance of this bulging suggests that it was caused by the meeting of two columns of air, and this explanation is consistent with Kuehn's conclusion that the rapidly moving drops set up an air current within the spray.

Figure 12 shows two sprays of the centrifugal type directed against each other in air having the same density as for Figure 11. In this case the spray tips do not continue to move forward after meeting, but a cloud of spray is projected at right angles to the spray axis. The results of Plasticine target tests with centrifugal-type sprays showed that their cores were composed of two distinct parts—a small central jet and a hollow cone surrounding the jet. Spark photographs showed that the central jet emerged before the hollow cone, but that it was soon overtaken by the cone. This jet is probably composed of the fuel trapped between the orifice and stem seat, so that it is injected without any whirling motion. Sprays of this type have a very low penetrating power; the maximum distance in air at a density of 1.1 pounds per cubic foot at which they would make a mark on the Plasticine was 0.75 inch. At a distance of 2.5 inches, therefore, all the drops must have come nearly to a stop with respect to the air, and so the results shown in Figure 12 are easily understood.

Summarizing, there were two extremes of spray interference: In one, the two sprays were not dispersed well enough for the fuel particles to pass between those of the opposite spray and in the other they were well dispersed, but the particles had lost nearly all velocity relative to the air. Most of the cases photographed fell between these two extremes.

Figures 13 to 15 show opposed-spray injections into air kept at constant density, but with different injection pressures and distances between the nozzles. It was necessary to use open nozzles for this series, but as previous tests (reference 5) have shown that sprays from these nozzles are similar to those from the injection values used in the variable air-density series, the results of the two series may be compared.

For both Figures 13 and 14 the distance between the nozzles was 3 inches, but the injection pressures were

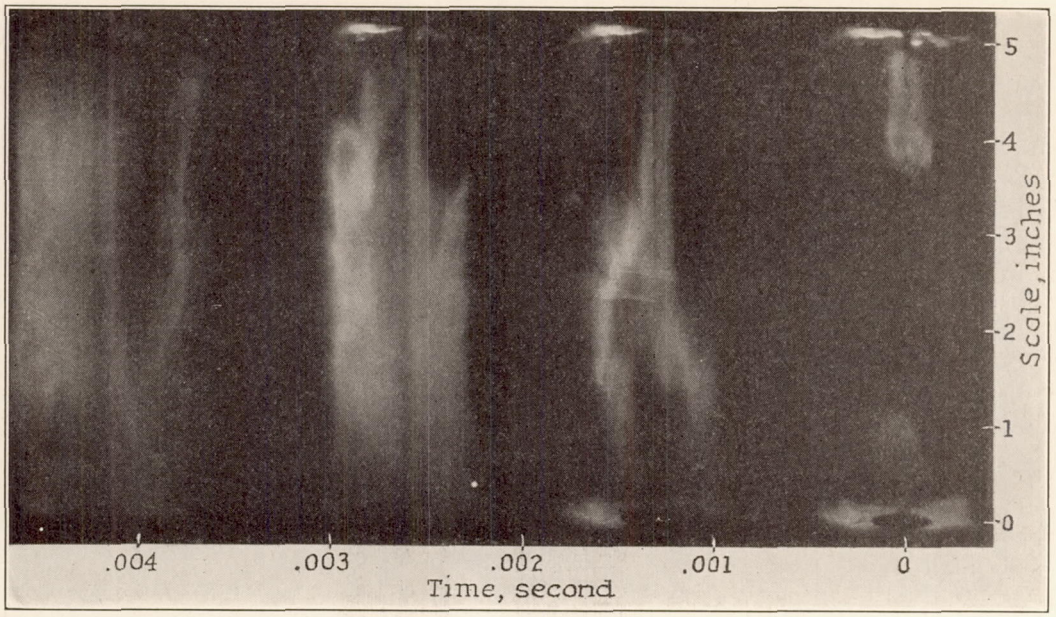


FIGURE 8.—Opposed fuel sprays injected into an evacuated chamber

Fuel-injection pressure, 4,000 pounds per square inch; chamber-air density, 0.0025 pound per cubic foot.

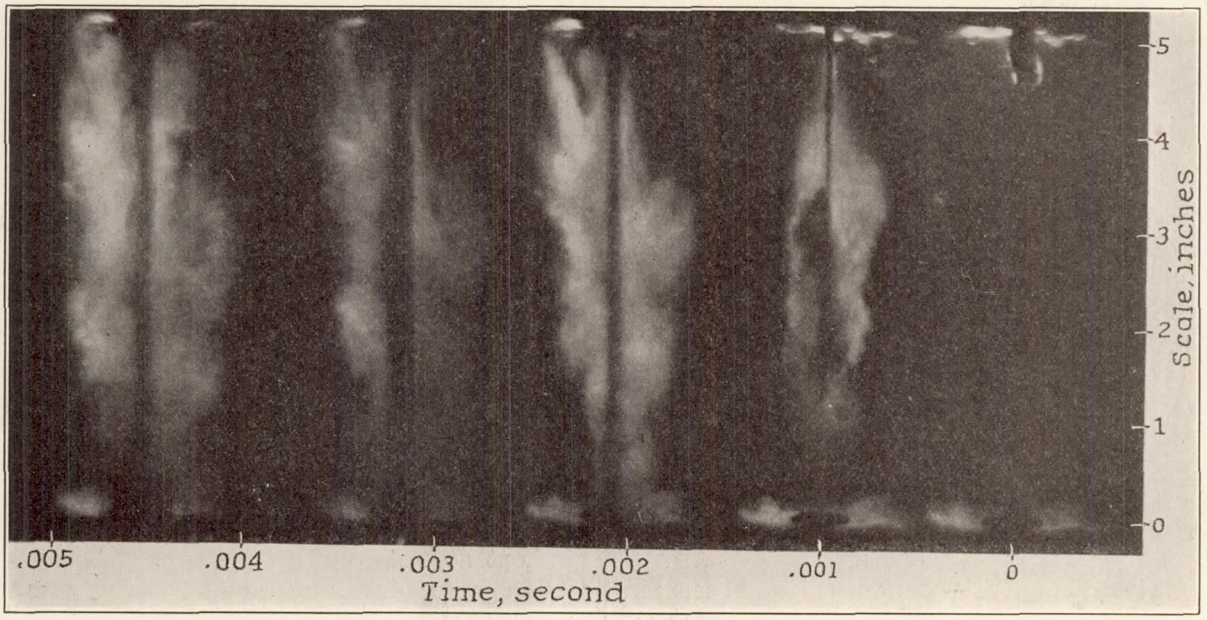


FIGURE 9.—Opposed fuel sprays injected into air at atmospheric density

Fuel-injection pressure, 4,000 pounds per square inch; chamber-air density, 0.076 pound per cubic foot.

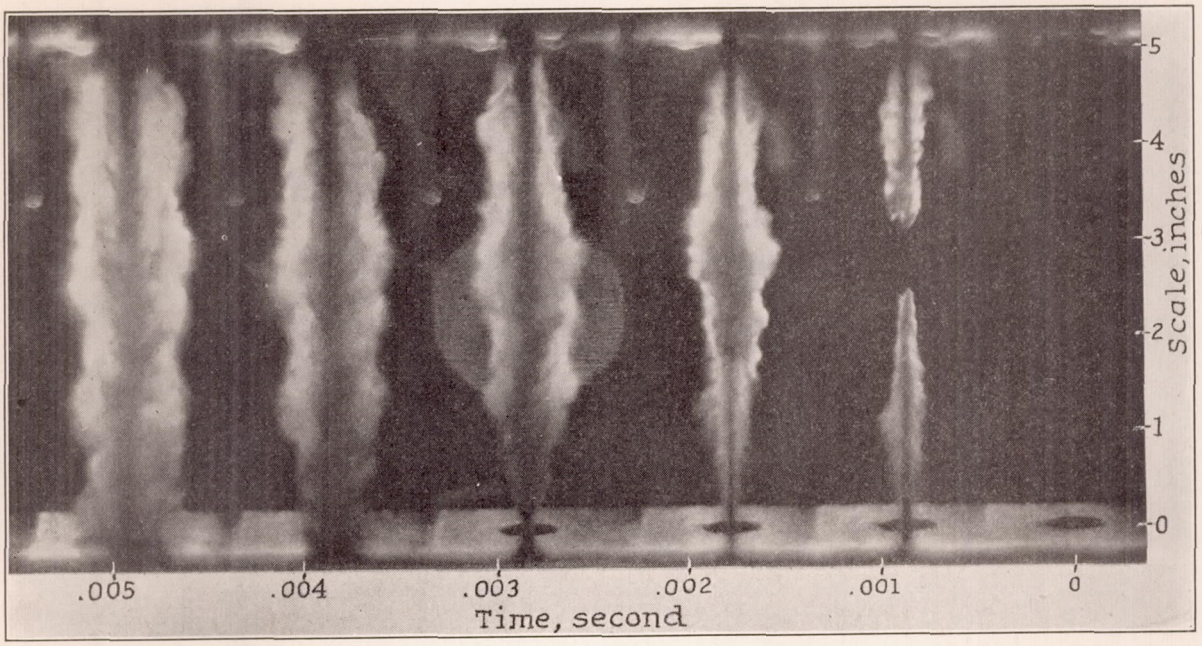


FIGURE 10.—Opposed fuel sprays injected into air having a density corresponding to that in an engine at a compression ratio of 7.9
Fuel-injection pressure, 4,000 pounds per square inch; chamber-air density, 0.060 pound per cubic foot.

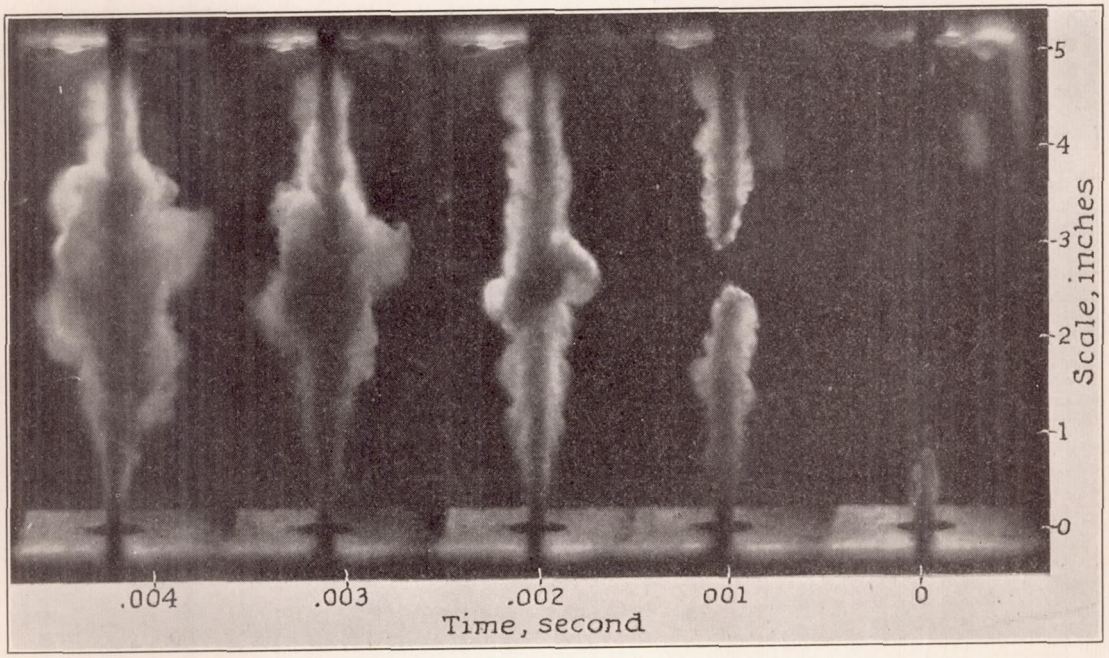


FIGURE 11.—Opposed fuel sprays injected into air having a density corresponding to that in an engine at a compression ratio of 14.5
Fuel-injection pressure, 4,000 pounds per square inch; chamber-air density, 1.1 pounds per cubic foot.

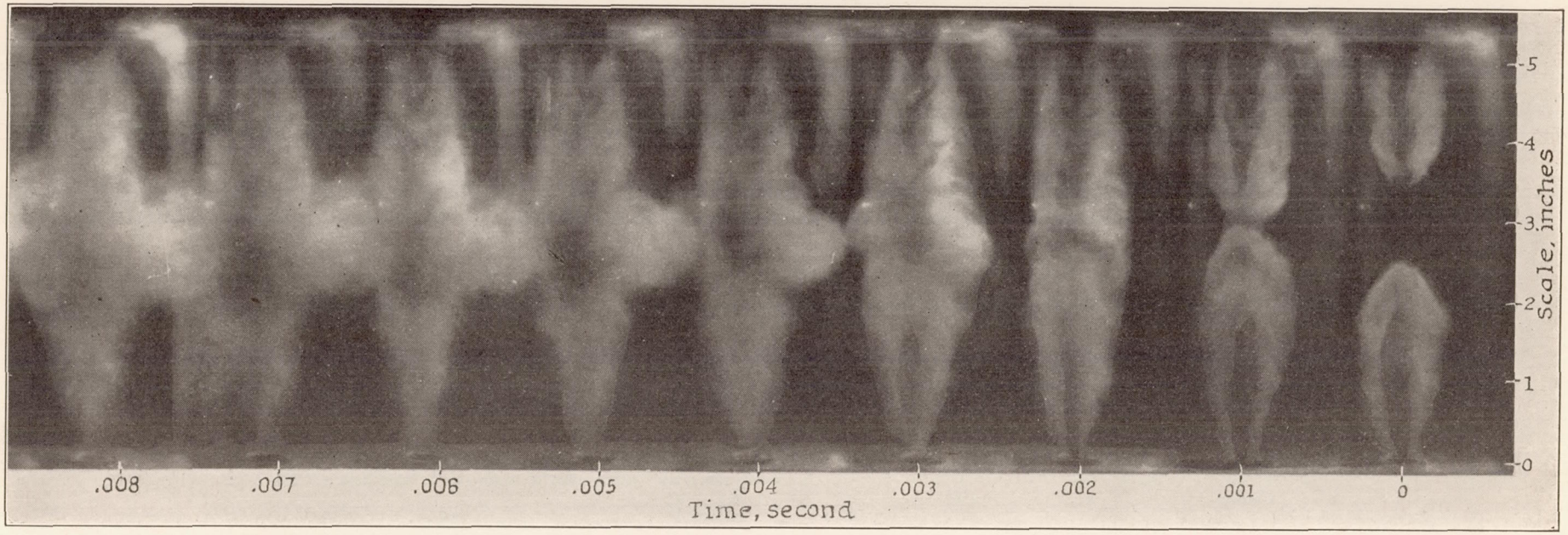


FIGURE 12.—Opposed centrifugal-type sprays

Fuel-injection pressure, 8,000 pounds per square inch; diameter of orifices, 0.022 inch; groove helix angles, 40°; chamber-air density, 1.1 pounds per cubic foot.

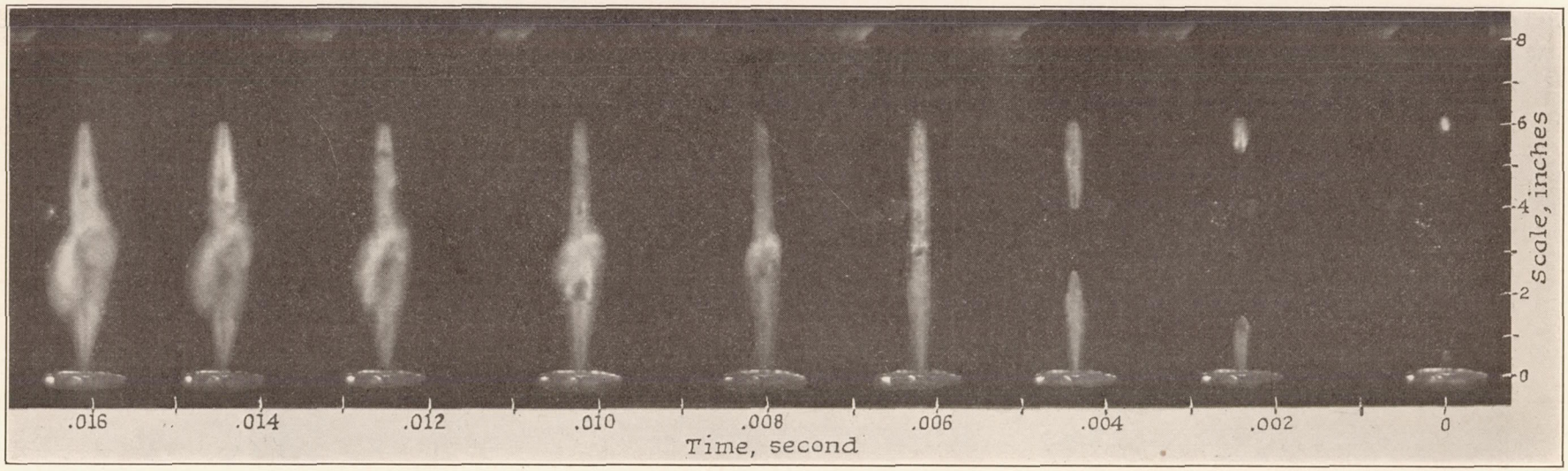


FIGURE 13.—Opposed sprays using a low injection pressure

Fuel-injection pressure, 500 pounds per square inch; chamber-air density, 1.1 pounds per cubic foot; distance between open nozzles, 3 inches.

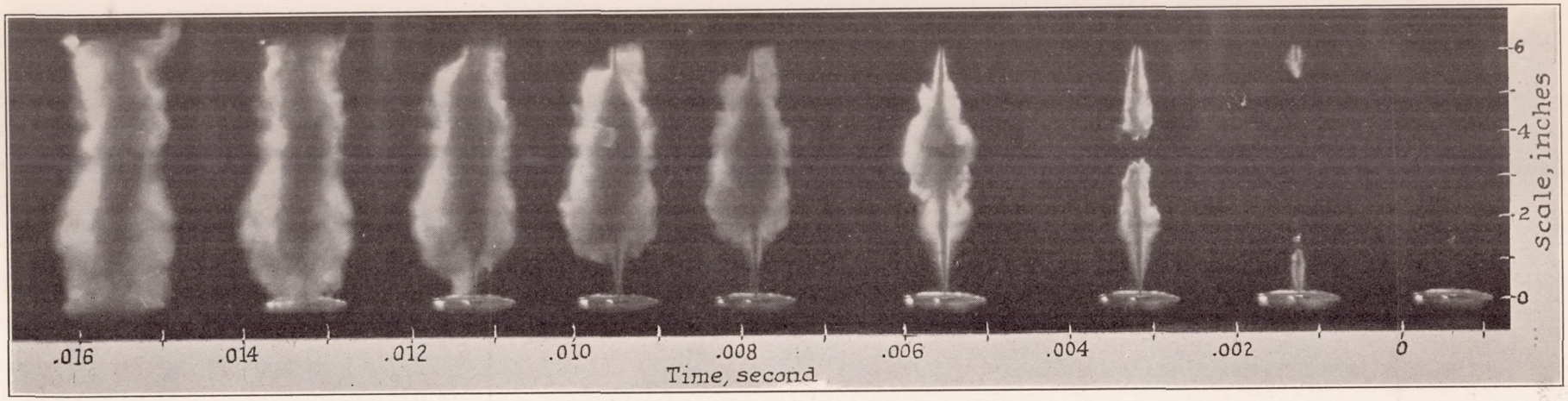


FIGURE 14.—Opposed sprays using a high injection pressure

Fuel-injection pressure, 4,000 pounds per square inch; chamber-air density, 1.1 pounds per cubic foot; distance between open nozzles, 3 inches.

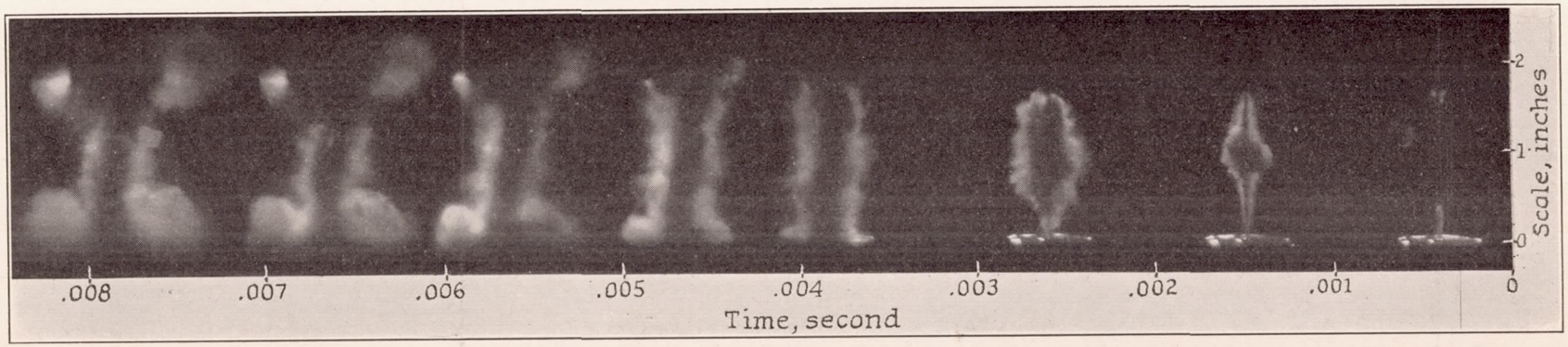


FIGURE 15.—Opposed sprays with the nozzles close together

Fuel-injection pressure, 4,000 pounds per square inch; chamber-air density, 1.1 pounds per cubic foot; distance between open nozzles, 1.5 inches.

500 and 4,000 pounds per square inch, respectively. With the lower injection pressure, the dispersion was apparently poor for the sprays showed the same type of interference as those of the previous series made at low air densities. With the higher air density, there was little interference, the results being similar to those shown in Figures 10 and 11.

Figures 11, 14, and 15 form a series in which the variable is the distance between the nozzles. In each case the photographs are quite similar. Notice in Figure 15 that the sprays pass through each other and rebound from the end of the opposite nozzle holder. This figure shows that even at 0.75 inch from the nozzle, a high-velocity spray in dense air is broken up.

EFFECT OF AIR JETS DIRECTED NORMAL TO FUEL SPRAYS

The photographs of fuel sprays having air jets directed normal to their axes were made to investigate the characteristics of the spray cores. The air jets deflected the spray envelopes leaving the cores exposed on one side. For Figures 16, 17, 19, and 20 the fuel was injected with an open nozzle, but for Figure 18 an automatic injection valve was used. In each case, the fuel-orifice diameter was 0.020 inch and the orifice diameter of the air jet was 0.040 inch. The photographs shown in Figures 16 to 18 were made with the chamber air at atmospheric density, and with the air jet approaching the fuel jet from the right. In Figure 16, the fuel in the envelope of the spray is shown being driven aside by the air jet, leaving the core exposed and deflected slightly. In Figure 17, for which the fuel-injection pressure was only half that for Figure 16, both the envelope and the core are shown being deflected by the air jet. More extensive experiments on the effect of high air velocities on fuel sprays have been reported by Rothrock in reference 10.

The point of intersection of the fuel and air jets was about one-quarter inch from the fuel nozzle for Figure 16, and about eleven-sixteenths inch for Figure 17. In both cases the distance from the air orifice was about one-sixteenth inch. For Figure 18, the distance from the fuel nozzle was about 3.5 inches, and from the air orifice about 1 inch. In Figure 18 the core is being nonuniformly deflected by the air jet, showing that the distribution of the fuel in the spray core was not uniform.

In Figures 19 and 20 are shown photographs of fuel and air jets intersecting about three-quarters inch from the fuel nozzle and one-quarter inch from the air orifice in a chamber where the air density was 1.1 pounds per cubic foot. For Figure 19 the air jet was coming from the right, but for Figure 20 it was moving directly away from the camera lens.

Different values of the air-jet injection pressure and the chamber-air pressure were used, but their ratio was always greater than 1.9, which is the critical value at which the velocity of the issuing jet becomes equal

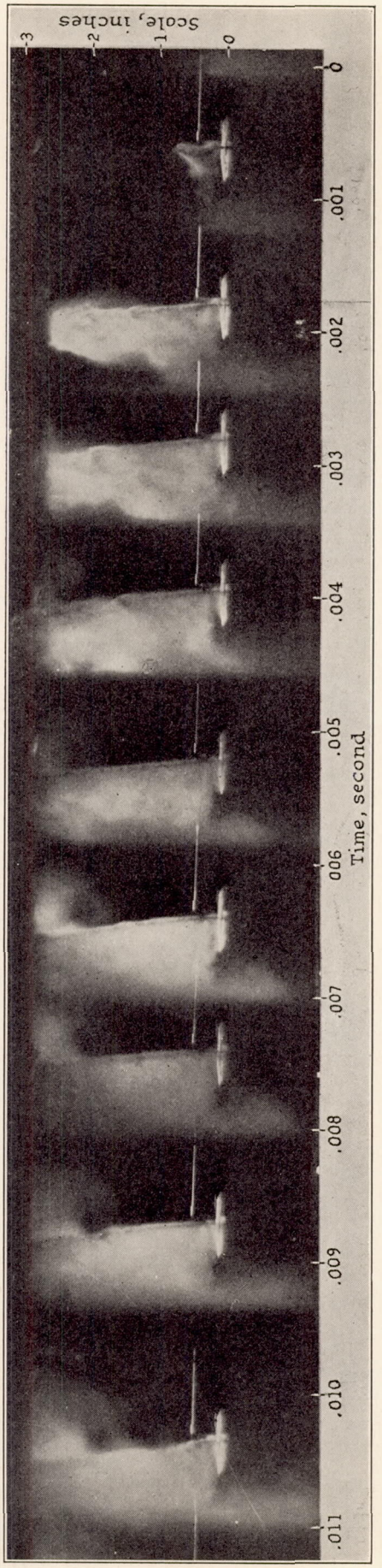


FIGURE 16.—Fuel spray with an air jet impinging at right angles from the right

Fuel-injection pressure, 1,000 pounds per square inch; air-jet injection pressure, 200 pounds per square inch; chamber-air density, 0.076 pound per cubic foot.

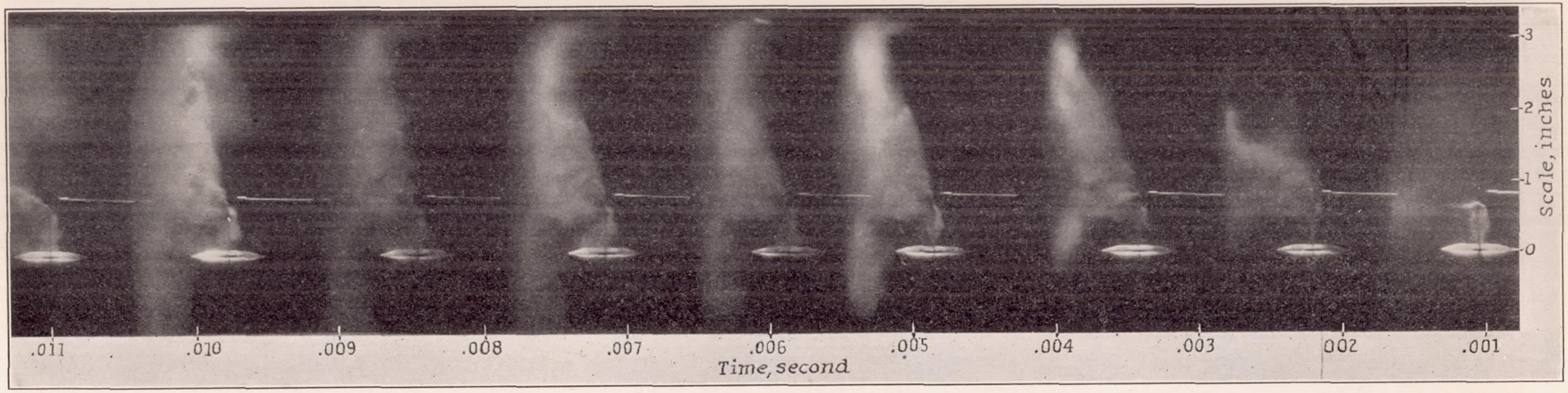


FIGURE 17.—Fuel spray with an air jet impinging at right angles from the right

Fuel-injection pressure, 500 pounds per square inch; air-jet injection pressure, 500 pounds per square inch; chamber-air density, 0.076 pound per cubic foot.

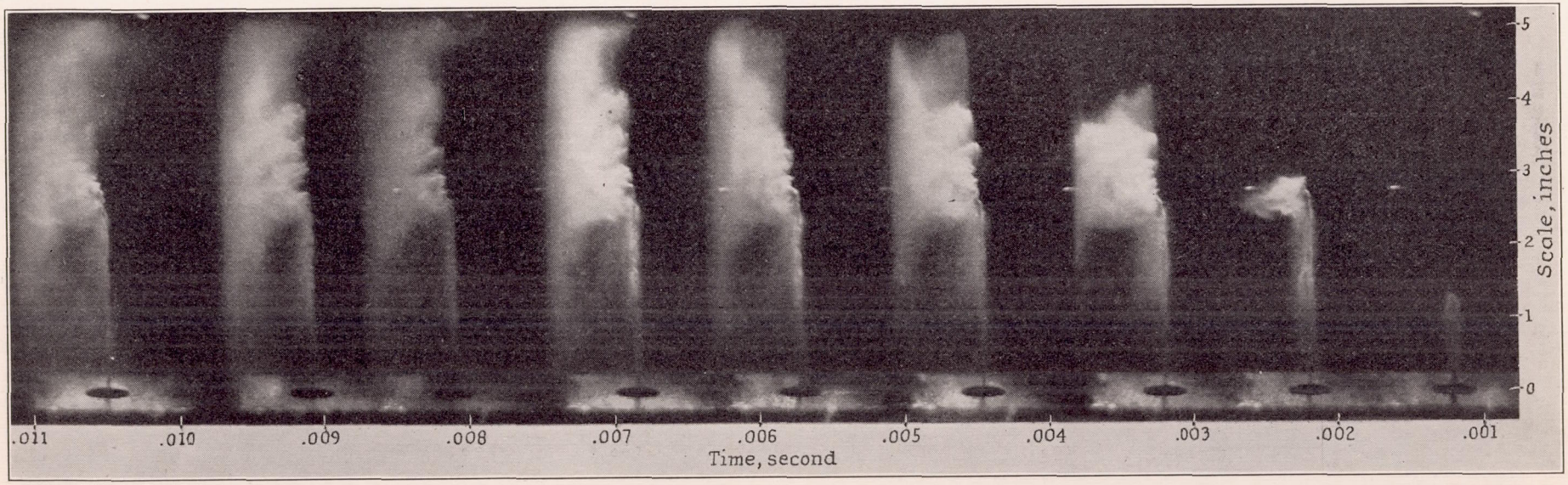


FIGURE 18.—Fuel spray with an air jet impinging at right angles from the right

Fuel-injection pressure, 500 pounds per square inch; air-jet injection pressure, 500 pounds per square inch; chamber-air density, 0.076 pound per cubic foot.

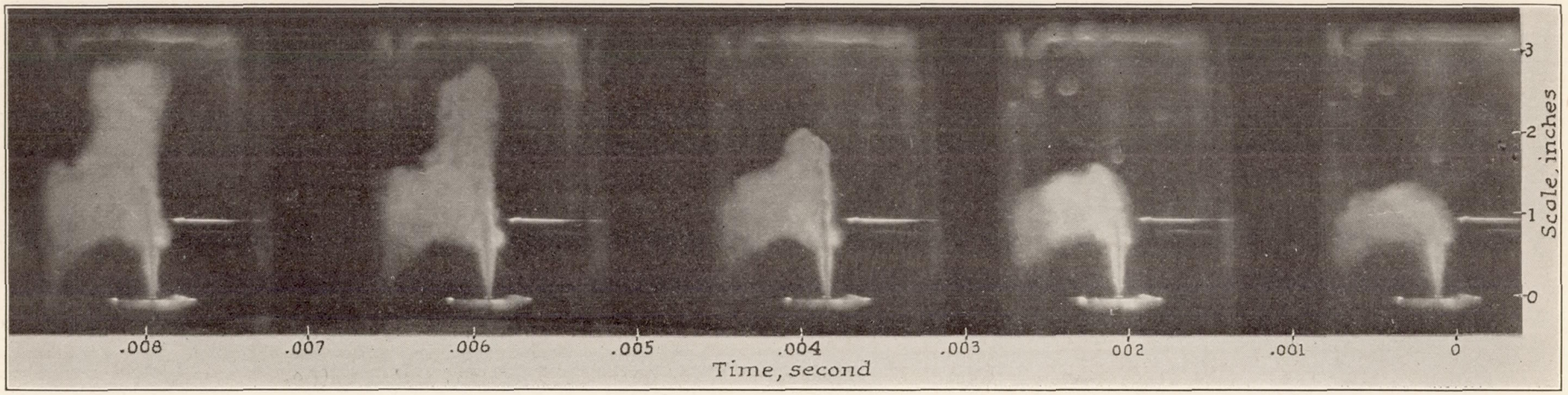


FIGURE 19.—Fuel and air jets intersecting at right angles. Air jet from the right

Fuel-injection pressure, 1,000 pounds per square inch; air-jet injection pressure, 500 pounds per square inch; chamber-air density, 1.1 pounds per cubic foot.

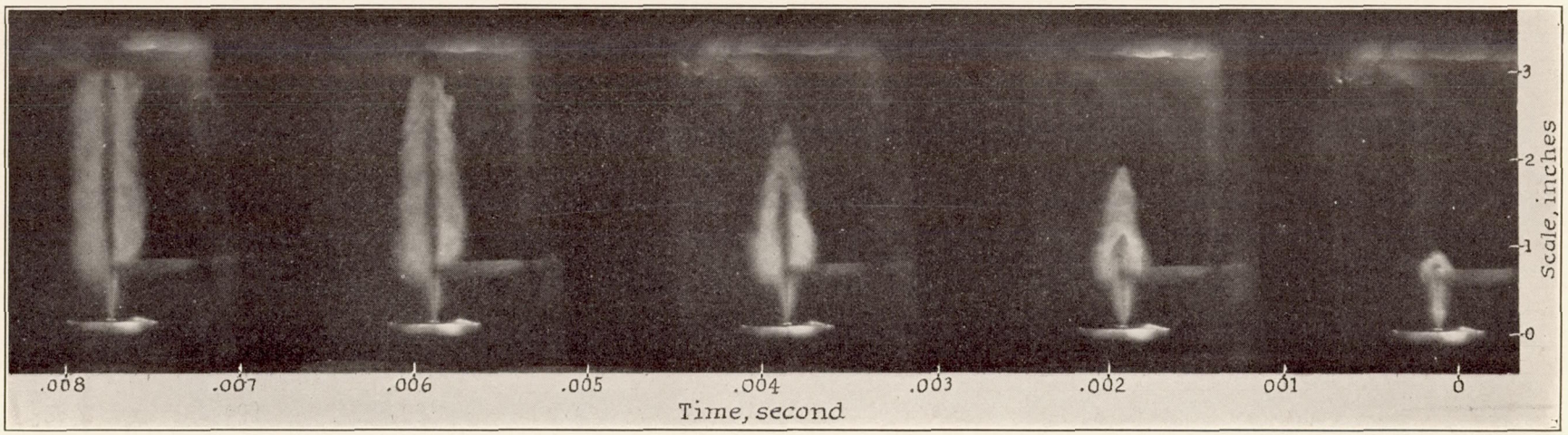


FIGURE 20.—Fuel and air jets intersecting at right angles. Air jet moving away from camera lens

Fuel-injection pressure, 500 pounds per square inch; air-jet injection pressure, 500 pounds per square inch; chamber-air density, 1.1 pounds per cubic foot.

to the velocity of sound. An increase in the value of this ratio will not increase the jet velocity. The velocities of the air jets in these experiments were therefore the same in all cases, and their energies depended only on the density of the air in the jets. Photographs made with different air-jet injection pressures, but with the same fuel-injection pressure and chamber-air density, showed little variation in the sprays. The lesser deflection of the core shown in Figure 16 as compared with Figure 17 should therefore be attributed to the higher fuel-injection pressure of the former rather than the lower air-jet injection pressure. Also, in comparing Figure 16 with Figure 19, the greater deflection of the latter should be attributed to the increased density of the air in the air jet, and to the decreased velocity of the fuel in the spray core.

CONCLUSIONS

1. The distribution of the fuel in both the core and the envelope of fuel sprays is very uneven.

2. Under engine-operating conditions, Diesel fuel injected through a 0.020-inch cylindrical nozzle is subdivided into particles by the time it has penetrated 0.75 inch.

3. Fully developed fuel sprays are composed of a central core and an outer envelope. The core is composed of fuel particles having a high velocity relative to the air in their immediate vicinity. As a result of this relative velocity a current of air is set up in the core. The envelope is composed of fuel particles that were formerly in the core, where they transferred their energy to the air until they lost most of their velocity relative to it, and were then forced out into the envelope by the on-coming column of air and fuel in the core behind them.

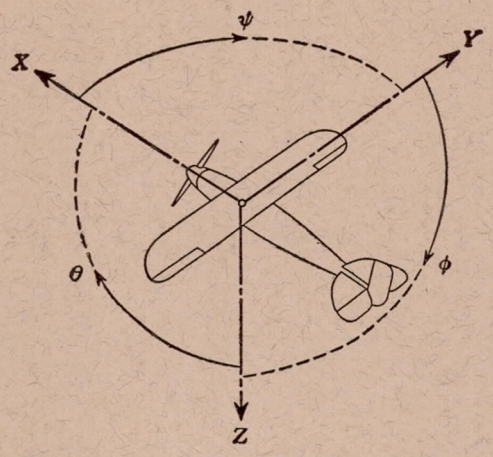
4. The shape of the central core varies with the density of the air, becoming shorter and thicker with increasing air density.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *February 13, 1932.*

REFERENCES

1. Schweitzer, P. H.: Factors in Diesel Spray-Nozzle Design in the Light of Recent Oil-Spray Research. Trans. A. S. M. E. OGP–52–15, 1930.
2. DeJuhasz, Kalman J.: Dispersion of Sprays in Solid-Injection Oil Engines. Trans. A. S. M. E. OGP–53–5, 1931.
3. Beardsley, E. G.: The N. A. C. A. Photographic Apparatus for Studying Fuel Sprays from Oil Engine Injection Valves and Test Results from Several Researches. T. R. No. 274, N. A. C. A., 1927.
4. A collective work: Photography as a Scientific Implement. Blackie and Son, Ltd. (London), pp. 266–267.
5. Rothrock, A. M., and Lee, D. W.: Some Characteristics of Fuel Sprays from Open Nozzles. T. N. No. 356, N. A. C. A., 1930.
6. Lee, Dana W.: The Effect of Nozzle Design and Operating Conditions on the Atomization and Distribution of Fuel Sprays. T. R. No. 425, N. A. C. A., 1932.
7. Lee, Dana W., and Spencer, Robert C.: Preliminary Photomicrographic Studies of Fuel Sprays. T. N. No. 424, N. A. C. A., 1932.
8. Kuehn, R.: Atomization of Liquid Fuels. Pt. III—Critical discussion of experimental results. Mixing the atomized fuel with air. T. M. No. 331. N. A. C. A., 1925.
9. Joachim, W. F., and Beardsley, E. G.: The Effects of Fuel and Cylinder Gas Densities on the Characteristics of Fuel Sprays for Oil Engines. T. R. No. 281, N. A. C. A., 1927.
10. Rothrock, A. M.: Effect of High Air Velocities on the Distribution and Penetration of Fuel Sprays. T. N. No. 376, N. A. C. A., 1931.

U. S. GOVERNMENT PRINTING OFFICE: 1932



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	ϕ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS} \qquad C_m = \frac{M}{qcS} \qquad C_n = \frac{N}{qbS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.

p, Geometric pitch.

p/D, Pitch ratio.

V', Inflow velocity.

V_s, Slipstream velocity.

T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$.

C_s, Speed power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$.

η, Efficiency.

n, Revolutions per second, r. p. s.

Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.